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GEOLOGY OF THE BIWABIK IRON FORMATION AND DULUTH COMPLEX

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The Biwabik Iron Formation is a layered sequence of iron-rich sedimentary rocks that was metamorphosed by intrusions of the Duluth Complex. The metamorphic recrystallization of iron-formation locally produced iron-rich amphiboles and other fibrous iron-silicate minerals. The presence of these minerals in iron-formation along the eastern Mesabi Iron Range and their potential liberation by iron mining has raised environmental health concerns. As a background to discussion of those concerns, we describe here the geologic setting of the Biwabik Iron Formation and the Duluth Complex, the stratigraphy of the iron-formation, the nature of the contact between the Biwabik Iron Formation and the Duluth Complex, and the general mineralogic and textural changes within iron-formation related to its progressive metamorphism by the Duluth Complex.

Geologic setting

Taconite mines of the Mesabi Iron Range are developed in the Biwabik Iron Formation, which is the type example of Lake Superior-type banded iron-formation. Banded iron-formations are a type of chemical sedimentary rock composed of alternating granular ("cherty") and laminated ("slaty") layers that were deposited in nearshore marine environments. All global occurrences of Lake Superior-type iron-formations were formed during the Paleoproterozoic era—a unique time in earth history approximately 2.4 to 1.6 billion years ago when photosynthesizing organisms are believed to have evolved and caused widespread oxygenation of the world's oceans and atmosphere. Along the 200-kilometer extent of the Mesabi Iron Range, the Biwabik Iron Formation occurs as a thick (100 to 250 meters), laterally extensive sheet that is slightly tilted to the south–southeast (Fig. 1). It conformably overlies the Pokegama Quartzite, a sandstone, siltstone, and conglomerate unit of variable thickness (0 to 100 meters), and is overlain by the Virginia Formation, a thick, but poorly exposed sequence of shale and graywacke. Collectively, this stratigraphic sequence (Pokegama Quartzite–Biwabik Iron Formation–Virginia Formation) is called the Animikie Group. A U-Pb zircon date from a tuffaceous unit in the nearby Gunflint Iron Formation yielded an age of 1,878.3 ± 1.3 million years (Fralick and others, 2002). The Gunflint and Biwabik Iron Formations were continuous prior to emplacement of the Duluth Complex, and thus the date is an approximate age for deposition of the Biwabik Iron Formation and associated Animikie strata. The Animikie Group rests unconformably on granite, greenstone, and other rocks of the Archean (greater than 2.4 billion years old) Superior Province, which constitutes the bedrock in most of northern Minnesota.

At the northeast terminus of the Mesabi Iron Range near Babbitt, the Biwabik Iron Formation and other units of the Animikie Group are abruptly truncated by gabbroic rocks of the Duluth Complex (Fig. 1). The coarse-grained igneous rocks of the Duluth Complex formed by the slow cooling and crystallization of mafic (dark colored) magmas that were intruded into subvolcanic chambers during a phase of continental rifting and voluminous igneous activity centered on present-day Lake Superior during the Mesoproterozoic era, about 1.1 billion years ago. The magma formed chambers several kilometers in thickness that were emplaced between a floor (or footwall) of Paleoproterozoic and Archean rocks, and a several-kilometers-thick cap of lavas (Fig. 2). Regional tilting to the east and erosion has removed the overlying volcanic rocks and exposed the arcuate lower contact of the intrusions against older footwall rocks.

Stratigraphy of the Biwabik Iron Formation

The Biwabik Iron Formation can be classified by texture into two generalized types of iron-formation: cherty materials, which are granular, massive, and typically but not always rich in quartz and iron oxides; and slaty materials, which are generally finely laminated, fine-grained, and composed mostly of iron silicates and iron carbonates (Table 1). Beds or groups of beds having granular or laminated attributes are interlayered on all scales. Despite this heterogeneity, the formation was divided by Wolff (1917) into four entities based on the ratio of "cherty" to "slaty" material present. These informal lithostratigraphic members are, from bottom to top: Lower Cherty, Lower Slaty, Upper Cherty, and Upper Slaty (Fig. 3). Within this classification scheme, slaty members typically contain about 40 percent laminated strata;

whereas, the cherty members contain 10 to 30 percent laminated material. Cherty members contain, on average, slightly more silica than the slaty members. Magnetite is the dominant iron mineral in cherty strata (magnetite is 31 percent FeO and 69 percent Fe_2O_3 by weight). Slaty members contain significant Al_2O_3, reflecting the presence of stilpnomelane—the only aluminum-bearing phase.

This stratigraphic scheme (Wolff, 1917) was designed to aid in understanding how various kinds of hematite-rich ores are distributed in the iron-formation. Except for the Intermediate Slate—a tuffaceous unit at the Lower Cherty–Lower Slaty boundary—the contacts between members are gradational and somewhat arbitrary. Therefore, the cherty–slaty nomenclature in itself was not a particularly useful mapping tool. Consequently, Grout and Broderick (1919) developed a modified scheme that created six stratigraphic units that could be easily recognized and mapped throughout the eastern Mesabi district, even where the rocks were appreciably metamorphosed (Fig. 4). The scheme was designed to estimate various resources and support the development of taconite mining at Babbitt in the early 1920s, and therefore emphasized the distribution of magnetite. Some 40 years later, Gundersen (1960) and Gundersen and Schwartz (1962) re-evaluated the stratigraphic setting in the eastern Mesabi district to further refine estimates of recoverable magnetite. They subdivided the iron-formation into 22 entities (units A-V on Figure 4), primarily on the basis of magnetite content and metamorphic mineralogy, and to a lesser extent on bedding characteristics. Their classification scheme emphasized small bed-to-bed differences, and consequently is best utilized to evaluate stratigraphy in drill cores. Although most of the 22 entities can be recognized in exposed bedrock, most are too thin to be mapped at a scale of 1:24,000. Therefore, other cartographic schemes, such as those of Griffin and Morey (1969) and Bonnichsen (1975), were developed utilizing bedding attributes as well as texture and mineralogy (Fig. 4).

The demonstrated utility of several stratigraphic classification schemes highlights the considerable heterogeneity that exists in the iron-formation, particularly in the eastern Mesabi district. That heterogeneity is further complicated by metamorphic processes associated with the emplacement of the Duluth Complex, which produced mineralogical changes within an aureole several miles wide.

Mining on the Mesabi Iron Range has been continuous since 1892. The first deposits that were mined—the so-called "natural ores"—consisted of material altered (oxidized and leached) by aqueous solutions along major and minor structures within the iron-formation, such as faults, fractures, folds, and select bedding-planes. More than 500 natural ore mines existed. After about 1955, production shifted to the use of taconite ores, composed of relatively unaltered magnetite-rich iron-formation. Most taconite ores have been and continue to be extracted from the Lower Cherty member of the Biwabik Iron Formation, with lesser amounts from the Upper Cherty and Slaty members (mined taconite intervals on Fig. 3b). Six taconite mines are currently operating.

Contact between the Biwabik Iron Formation and the Duluth Complex

The nature of the intrusive contact between the gabbroic rocks of the Duluth Complex and the Biwabik Iron Formation is fairly well known from exposures in the Dunka Pit and from hundreds of drill holes that penetrated the footwall of the Duluth Complex. The corresponding drill cores have been acquired over the past 50 years in support of exploration for copper-nickel-platinum group element (Cu-Ni-PGE) sulfide deposits in the basal part the complex. Most of this core, which is stored at the Minnesota Department of Natural Resources core repository in Hibbing, has been relogged and analyzed by geologists at the University of Minnesota's Natural Resources Research Institute. These subsurface data indicate that the contact between the gabbroic rocks of the Duluth Complex and the Animikie Group sedimentary rocks has a southeasterly dip that is steeper than the dip of bedding in the sedimentary rocks. Thus, the gabbro has cut progressively downward across the Virginia Formation, Biwabik Iron Formation, and Pokegama Quartzite, and ultimately down to Archean rocks (predominantly granite). This sequential crosscutting is also evident at the surface along the northwestern basal contact of the gabbro (Fig. 1). In areas of closely spaced drilling, it is clear that downcutting occurred in a stair-step fashion, with some of the major declines corresponding to faults in the footwall rocks (Fig. 2).

On a more detailed scale, the nature of the contact is locally complex. As observed in some surface exposures and areas of detailed drilling, strongly recrystallized and intensely deformed sedimentary rocks are complexly interdigitated with the gabbro. Some partial melting of the sedimentary rocks is also common. The complexities of the contact likely resulted from the intense heating of the sedimentary rocks, which not only resulted in their recrystallization, but also caused the rocks to become ductile, and thus easily deformed with minor magmatic and tectonic stresses. In the basal zone of the gabbro, inclusions of sedimentary rocks are abundant and commonly so strongly recrystallized and partially melted that they are difficult to distinguish from the host gabbro. Remnants of Biwabik Iron Formation inclusions are recognized locally only by the abundance of iron oxide in the gabbro. The assimilation of sulfide-bearing sedimentary rocks is thought to be the main process responsible for the Cu-Ni-PGE mineralization locally within the basal gabbro.

Progressive metamorphism of the Biwabik Iron Formation

Conductive cooling of the gabbroic magma resulted in thermal metamorphism of the Biwabik Iron Formation and associated rocks underlying the Duluth Complex. The effects of this metamorphism are most pronounced within a few kilometers of the contact zone, and progressively decrease southwestward away from the contact. Four generalized metamorphic zones can be delineated west of the Duluth Complex (French, 1968). These are shown on Figure 3 and summarized below.

Zone 1—"Unaltered" taconite extends westward from the first appearance of metamorphic minerals and textures. It is generally considered protolith to more metamorphosed rocks to the east. The unaltered rocks contain quartz, magnetite, hematite, siderite, ankerite, talc, and iron-silicates (chamosite, greenalite, minnesotaite, stilpnomelane, and talc). The minerals quartz, hematite, siderite, chamosite, greenalite, and some magnetite are considered primary minerals. Textures of the others—talc, minnesotaite, stilpnomelane, and most magnetite—indicate crystallization from secondary diagenetic processes or early metamorphism unrelated to emplacement of the Duluth Complex.

Zone 2—Transitional taconite contains mineral assemblages that are similar to unaltered taconite, but differs by the extensive replacement of quartz and ankerite and the reduction of hematite to magnetite in the iron-formation, and the appearance of clinozoisite in the subjacent Pokegama Quartzite.

Zone 3—Moderately metamorphosed taconite is characterized by the development of the iron-rich amphiboles grunerite and cummingtonite, at the expense of original iron carbonates and silicates, and the associated production of calcite.

Zone 4—Highly metamorphosed taconite is completely recrystallized to a metamorphic fabric composed mainly of quartz, iron amphiboles (grunerite-cummingtonite, hornblende), iron pyroxenes (hedenbergite, ferrohypersthene), magnetite, and rare fayalite and calcite.

Despite the heterogeneity of the iron-formation, some of the stratigraphic framework established from exposures and drilling in the relatively unaltered rocks of Zone 1 can be correlated with more metamorphosed equivalent strata in zones closer to the Duluth Complex. Remarkably, even in the highest metamorphic grade, the iron-formation locally retains relics of original sedimentary textures. Small intrusive dikes and veins in the contact zone may represent introduction of magma and some volatiles from the adjacent Duluth Complex (Gundersen and Schwartz, 1962); however, studies by French (1968), Morey and others (1972), and Bonnichsen (1975) indicate that metamorphism was isochemical, involving the loss of H_2O and CO_2, but no significant introduction of components from the adjacent gabbro. The loss of volatiles during late stages of metamorphism produced minor and localized, hydrous, retrograde minerals including cummingtonite.

It is generally assumed that the magma associated with the Duluth Complex was approximately 1,200°C at the time of emplacement. However, the temperatures attained by the Animikie Group during that event in the various metamorphic zones are difficult to estimate. Diopside occurs in some of the carbonate-rich rocks at the top of the iron-formation just east of Mesaba (Griffin and Morey, 1969), and Gundersen and Schwartz (1962) reported wollastonite near Babbitt, about 4 miles to the east. Experimental work reported in French (1968) indicated that these phases formed at 500 to 600°C for diopside, and 600 to 700°C for wollastonite, in the pressure range of 1,000 to 3,000 bars (P_{H2O}). Non-calcareous rocks in the Virginia Formation containing cordierite, biotite, muscovite, and quartz also indicate a temperature in the range of 500 to 700°C at about 1,000 bars (P_{H2O}; Labotka and others, 1981). Temperatures in this order of magnitude are further indicated by the work of Perry and Bonnichsen (1966, p. 525), who suggested on the basis of oxygen-isotope fractionation in magnetite-quartz pairs that the maximum temperature attained by the iron-formation at the east end of the district near Dunka River was about 700 to 750°C. Mineralogic zoning described by French (1968) indicated that metamorphic temperatures progressively decreased to the west in a general direction away from the present location of the contact with the Duluth Complex. He concluded that grunerite formed at temperatures below 400°C, probably in the range of 300 to 400°C (French, 1968, p. 87).

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FIGURE CAPTIONS

Figure 1. Simplified bedrock geologic map of the Mesabi Iron Range and adjacent Duluth Complex. The location of the cross-section depicted on Figure 2 is labeled.

Figure 2. Schematic geologic section showing the basal contact of the Duluth Complex against older host rocks including the Biwabik Iron Formation, and capped by volcanic rocks of the North Shore Volcanic Group.

Figure 3. Simplified geologic map (A) showing locations of taconite mines, drill holes, and contact metamorphic zones from French (1968); and stratigraphic section (B) showing subdivision of the Biwabik Iron Formation and approximate mined taconite intervals at each locality. Stratigraphic units are measured from a horizontal line approximating the position of the Intermediate Slate at the Lower Cherty–Lower Slaty boundary. Modified from a compilation of drill holes by H. Djerlev—Hibbing Taconite (Meineke, 1993); and from mine sections compiled by M. Severson (Zanko and others, 2003).

Figure 4. Schematic representation of various stratigraphic classifications of the Biwabik Iron Formation and corresponding relative mineralogic abundance.

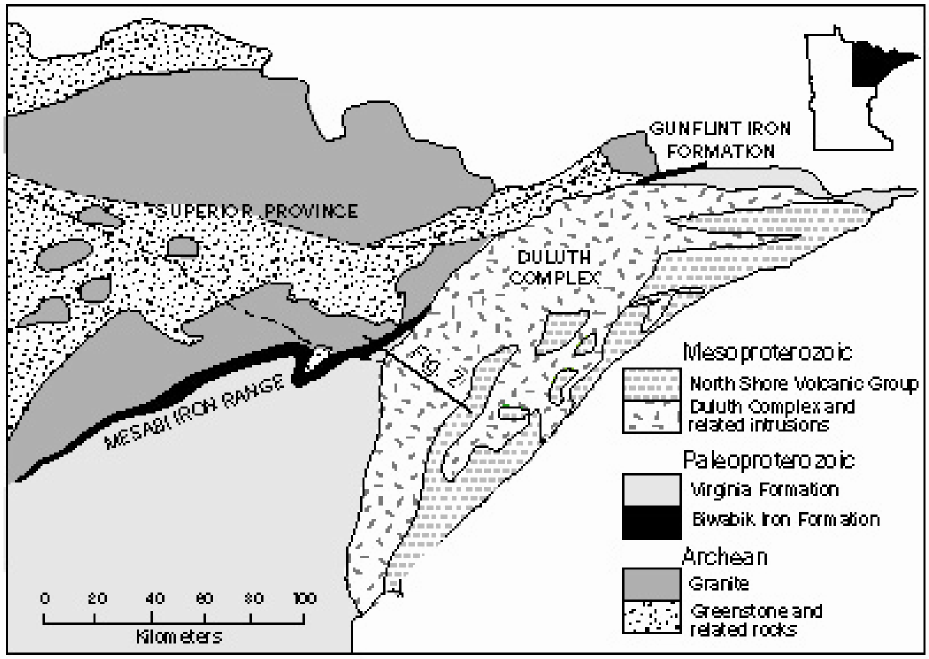

Figure 1.

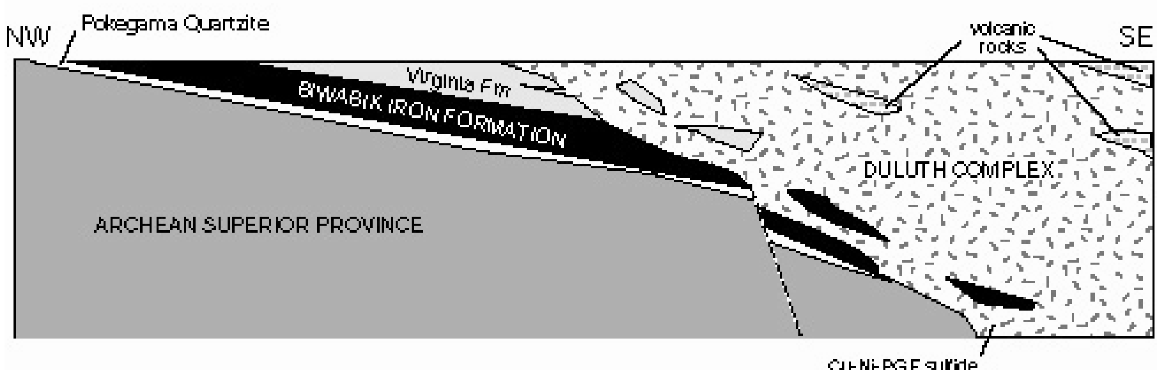

Figure 2.

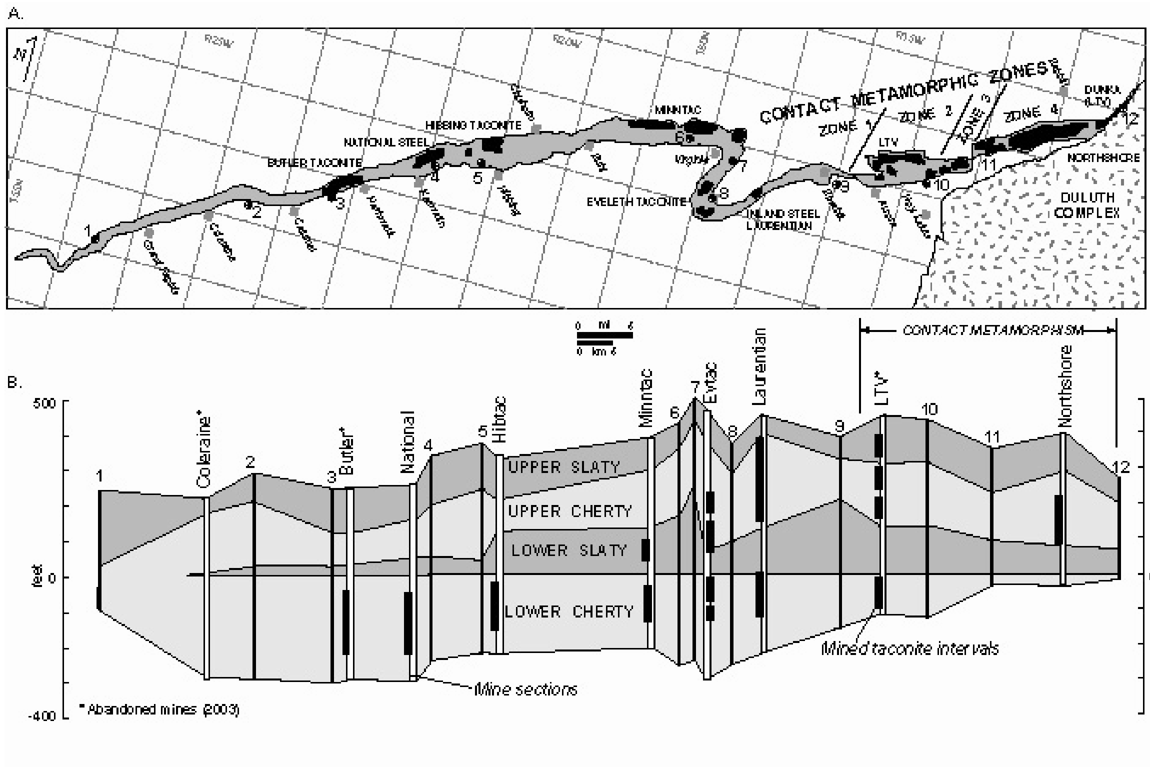
A.
CONTACT METAMORPHIC ZONES
ZONE 1
ZONE 2
ZONE 3
ZONE 4
MINNTAC
HIBBING TACONITE
NATIONAL STEEL
BUTLER TACONITE
EVELETH TACONITE
INLAND STEEL LAURENTIAN
LTV
DUNKA (LTV)
NORTHSHORE
DULUTH COMPLEX
B.
CONTACT METAMORPHISM
Coleraine*
Butler*
National
Hibtac
Minntac
Evtac
Laurentian
LTV*
Northshore
UPPER SLATY
UPPER CHERTY
LOWER SLATY
LOWER CHERTY
feet
500
0
-400
Mine sections
Mined taconite intervals
* Abandoned mines (2003)

Figure 3.

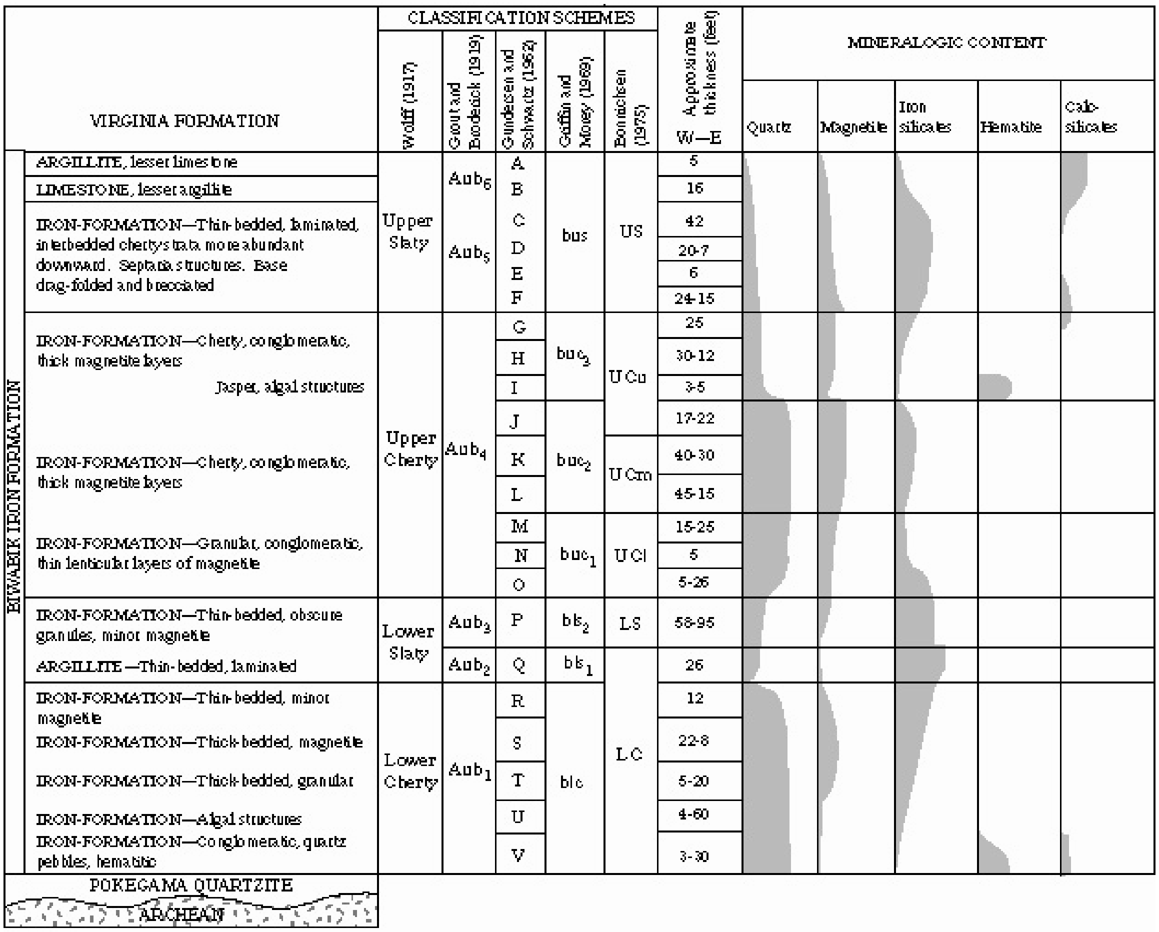
CLASSIFICATION SCHEMES
Wolff (1917)
Grout and Broderick (1919)
Gundersen and Schwartz (1962)
Griffin and Morey (1969)
Bonnichsen (1975)
Approximate thickness (feet) W—E
MINERALOGIC CONTENT
Quartz
Magnetite
Iron silicates
Hematite
Calc-silicates
VIRGINIA FORMATION
BIWABIK IRON FORMATION
ARGILLITE, lesser limestone
LIMESTONE, lesser argillite
IRON-FORMATION—Thin-bedded, laminated, interbedded cherty strata more abundant downward. Septaria structures. Base drag-folded and brecciated
IRON-FORMATION—Cherty, conglomeratic, thick magnetite layers
Jasper, algal structures
IRON-FORMATION—Cherty, conglomeratic, thick magnetite layers
IRON-FORMATION—Granular, conglomeratic, thin lenticular layers of magnetite
IRON-FORMATION—Thin-bedded, obscure granules, minor magnetite
ARGILLITE—Thin-bedded, laminated
IRON-FORMATION—Thin-bedded, minor magnetite
IRON-FORMATION—Thick-bedded, magnetite
IRON-FORMATION—Thick-bedded, granular
IRON-FORMATION—Algal structures
IRON-FORMATION—Conglomeratic, quartz pebbles, hematitic
POKEGAMA QUARTZITE
ARCHEAN
Upper Slaty
Upper Cherty
Lower Slaty
Lower Cherty
Aub6
Aub5
Aub4
Aub3
Aub2
Aub1
A B C D E F G H I J K L M N O P Q R S T U V
bus
buc3
buc2
buc1
bls2
bls1
blc
US
UCu
UCm
UCl
LS
LC
5
16
42
20-7
6
24-15
25
30-12
3-5
17-22
40-30
45-15
15-25
5
5-26
58-95
26
12
22-8
5-20
4-60
3-30

Figure 4.

Table 1. MINERALS IN THE BIWABIK IRON FORMATION

Iron oxide minerals	
Hematite	Fe_2O_3
Magnetite	Fe_3O_4
Carbonate minerals	
Ankerite	$Ca(Mg, Fe)(CO_3)_2$
Siderite	$FeCO_3$
Dolomite	$CaMg(CO_3)_2$
Kutnohorite-ferroan Kutnohorite	$Ca(Mn, Mg, Fe)(CO_3)_2$
Calcite	$CaCO_3$
Silicate and iron silicate minerals	
Quartz	SiO_2
Chlorite group	
Chamosite	$(Fe^{2+}, Al, Mg)_6(Si, Al)_4O_{10}(OH)_8$
Minnesotaite	$Mg_3(Si_2O_5)_2(OH)_2$
Talc	$Mg_3Si_4O_{10}$ $(OH)_{12}$
Brittle mica group	
Stilpnomelane	$K(Fe^{2+}, Fe^{3+}, Al)_{10}Si_{12}O_{30}(O, OH)_{12}$
Mica group	
Biotite	$K_2(Fe^{2+}, Mg)_{6-4}(Fe^{3+}, Al, Ti)_{0-2}(Si_{6-5}, Al_{2-3})O_{20-22}(OH, F)_{4-2}$
Muscovite	$K_2Al_4(Si_6Al_2)O_{20}(OH)_4$
Serpentine group	
Greenalite	$(Fe^{2+}, Fe^{3+}, Mg)_6Si_4O_{10}(OH)_8$
Amphibole group	
Grunerite	$(Fe^{2+}, Mg, Mn)_7Si_8O_{22}(OH)$
Cummingtonite	$(Mg, Fe^{2+})_7Si_8O_{22}(OH)_2$
Hornblende	$Ca_2Na(Mg, Fe^{2+}, Fe^{3+}, Al)_5(Si_{6-7}, Al_{2-1})O_{22}(OH, F)_2$
Actinolite	Ca_2 $(Mg, Fe^{2+})_5[Si_8O_{22}](OH)_2$
Pyroxene group	
Hedenbergite	$Ca(Mg,Fe)[Si_2O_6]$
Enstatite-Ferrosilite series	$(Mg,Fe^{2+})[SiO_3]$
Diopside	$CaMgSi_2O_6$ to $Ca(Mg, Fe^{2+})Si_2O_6$
Cordierite group	
Cordierite	$(MgFe^{2+})_2Al_4Si_5O_{18}$
Olivine group	
Fayalite	$(Fe, Mg)_2SiO_4$ to Fe_2SiO_4
Garnet group (reported in McSwiggen and Morey, this volume)	
Almandine	$Fe_3Al_2Si_3O_{12}$
Andradite	$Ca_3Fe_2Si_3O_{12}$